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EFFECT OF INLET-AIR TEMPERATURE AND CYLINDER DISPLACEMENT ON CHARGE TEMPERATURE OF INTERNAL-COMBUSTION ENGINES

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RESTRICTED BULLETIN

EFFECT OF INLET-AIR TEMPERATURE AND CYLINDER DISPLACEMENT ON CHARGE TEMPERATURE OF INTERNAL-COMBUSTION ENGINES

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SUMMARY

Object. - To determine the effect of inlet-air temperature and cylinder displacement on the charge temperature of an internal-combustion engine at the end of the induction stroke.

Scope. - The heating effect of cylinder walls was estimated by determining the effect of inlet-air temperature on air consumption of engines operated at constant inlet-air pressure. Tests were run on the following five single-cylinder test units: an engine of 17.6-cubic-inch displacement; a CFR engine of 37.4-cubic-inch displacement; a Lycoming cylinder of 102.8-cubic-inch displacement; an Allison V-1710 cylinder of 142.5-cubic-inch displacement; and a Wright 1820 G200 cylinder of 202.5-cubic-inch displacement.

The actual value of the cylinder-charge temperature has not been determined in this investigation, but the variation of the charge temperature with the inlet-air temperature and the effect of cylinder size on these variations have been found.

Summary of results. - Results of tests are summarized as follows:

1. The cylinder-charge temperature at the end of the induction stroke appeared to be a linear function of the inlet-air temperature.

2. The rate of change of cylinder-charge temperature at the end of the induction stroke with the inlet-air temperature varied with the cylinder displacement according to the equation:

$$\log_e B = -\frac{2.32}{\sqrt[3]{D}}$$

where

B rate of change of cylinder-charge temperature at end of induction stroke with inlet-air temperature

D cylinder displacement, cubic inches

INTRODUCTION

One of the main problems in the field of fuel knock rating is the correlation of knock tests obtained with various engine cylinders. Tests of the same fuel in different cylinders at the same conditions of compression ratio, engine speed, inlet-air temperature, coolant or head temperature, and spark advance show large differences in knock limits. One of the contributing causes to the disagreement between cylinders is the difference in heat transfer from the cylinder to the charge.

The present study is part of a program to correlate knock tests among various cylinders and to determine the relative effect of engine variables on the knock limit of fuels. The specific object of this investigation is to determine the effects of inlet-air temperature and cylinder displacement on the charge temperature at the end of the induction period. The results are primarily intended to aid in the analysis of knock-test data.

The following equation from reference 1 relates cylinder-charge temperature, inlet-air temperature, and cylinder-wall temperature:

$$T_c = T_a + A \left(T_w - T_a\right) \qquad (1)$$

or

$$T_c = T_a \left(1 - A\right) + T_w A$$

where

T_c charge temperature

T_a inlet-air temperature

T_w mean inside temperature of cylinder walls

A constant

Reference 1 does not give a formal derivation of equation (1). A derivation given in the appendix of the present report gives the following equations:

$$T_c = T_a B + T_w' (1 - B) \qquad (2)$$

and

$$\log_e \frac{1}{B} = \frac{H}{\sqrt[3]{D}} \tag{3}$$

where B and H are constant. Equations (1) and (2) are equivalent and $B = 1 - A$.

Experimental evidence was gathered in the present study to verify the form of equation (2) and to evaluate the constant H in equation (3). The data do not permit the evaluation of T_c.

The data for this study were obtained by the NACA at the Langley Memorial Aeronautical Laboratory at Langley Field, Va., and at the Aircraft Engine Research Laboratory at Cleveland, Ohio.

APPARATUS

Tests were conducted on an engine of 17.6-cubic-inch displacement designed by the Ethyl Corporation, a CFR engine, a Lycoming O-1230 cylinder, an Allison V-1710 cylinder, and a Wright 1820 G200 cylinder. The Wright cylinder was air-cooled and the other four cylinders were liquid-cooled. The test setups are described in the succeeding paragraphs.

<u>17.6 engine.</u> - In the 17.6-engine tests the standard intake elbow for the AFD 3-C fuel-test engine was used. A small surge tank with a volume of 415 cubic inches was directly connected to the intake elbow. Air flow was measured with a thin-plate-orifice meter. Fuel was injected into the air at the intake elbow.

The valve timing was as follows:

Intake opens, degrees A.T.C.	10
Intake closes, degrees A.B.C.	40
Exhaust opens, degrees B.B.C.	40
Exhaust closes, degrees A.T.C.	15

<u>CFR engine.</u> - The tests with the modified CFR engine of 37.4-cubic-inch displacement were conducted with the apparatus described in reference 2. A fuel-injection nozzle was inserted into a special opening in the intake manifold at a point directly opposite the intake port of the engine. The nozzle pointed directly at the center of the intake port and was located 3 inches from the port. Injection started at 40° A.T.C. on the intake stroke. The combustion-air surge tank had a volume of 450 cubic inches. The inlet-air pressure was measured by a

mercury manometer connected to the surge tank. The inlet-air temperature was measured by a mercury-in-glass thermometer located between the surge tank and the intake manifold.

An evaporative cooling system was used and the coolant temperature was at the boiling point of the coolant. The desired boiling points were obtained by using mixtures of water and ethylene glycol.

The valve timing was as follows:

Intake opens, degrees A.T.C.	10
Intake closes, degrees A.B.C.	34
Exhaust opens, degrees B.B.C.	40
Exhaust closes, degrees A.T.C.	15

<u>Lycoming cylinder</u>. - A Lycoming O-1230 cylinder with a 102.8-cubic-inch displacement was installed on a CUE crankcase. A surge tank with a volume of 17,300 cubic inches was connected to the intake port of the cylinder with a $2\frac{5}{16}$-inch-diameter intake pipe 12 inches long. Fuel was sprayed into the intake pipe through a nozzle $4\frac{3}{8}$ inches from the intake port of the engine.

The valve timing was as follows:

Intake opens, degrees B.T.C.	31
Intake closes, degrees A.B.C.	67
Exhaust opens, degrees B.B.C.	61
Exhaust closes, degrees A.T.C.	37

<u>Allison cylinder</u>. - An Allison V-1710 cylinder of 142.5-cubic-inch displacement was installed on a CUE crankcase. The test equipment was identical with the Lycoming setup except for the cylinder, the piston, and the crankshaft throw.

The valve timing was as follows:

Intake opens, degrees B.T.C.	48
Intake closes, degrees A.B.C.	62
Exhaust opens, degrees B.B.C.	76
Exhaust closes, degrees A.T.C.	26

<u>Wright cylinder</u>. - A Wright 1820 G200 air-cooled cylinder of 202.5-cubic-inch displacement was mounted on a CUE crankcase. The cylinder was fitted with commercial aircraft baffles and mounted in a special cowling. The rest of the test apparatus was identical with the Lycoming setup except for the cylinder, the piston, and the crankshaft throw.

The valve timing was as follows:

Intake opens, degrees B.T.C.	14
Intake closes, degrees A.B.C.	40
Exhaust opens, degrees B.B.C.	74
Exhaust closes, degrees A.T.C.	21

TEST PROCEDURE

The inlet-air pressure was adjusted equal to the exhaust pressure and the pressures were held constant during all tests. Test conditions for each engine are given in figures 1 to 5. In the case of the four liquid-cooled cylinders, the coolant temperatures were held constant in any one test, the inlet-air temperature was varied, and the air flow at each temperature was measured.

The air-cooled Wright-cylinder tests were similar to the liquid-cooled cylinder tests with the exception of cylinder-cooling control. In this series of tests, the cooling-air pressure drop across the engine cylinder and the cooling-air temperature were held constant during any one run. Runs were taken at two different cooling-air pressure drops.

ANALYSIS OF RESULTS

The variation with inlet-air temperature of the air flow into an engine cylinder at constant inlet-air pressure is a measure of the variation of cylinder-charge temperature with inlet-air temperature, provided that the inlet-air temperature and the coolant temperature do not affect the cylinder-charge pressure at the instant of inlet-valve closing and provided that the effects of supercharging which result from the inertia of the air in the intake pipe are small.

The temperature of the cylinder charge at the instant of inlet-valve closure is proportional to the reciprocal of the charge weight; therefore, the reciprocal of the air flow measured in the present tests was plotted against the measured absolute inlet-air temperature (figs. 1 to 5). The fact that straight lines fit the data indicate that the form of equation (2) is correct.

Evaluation of B. - The reciprocal of the air flow to the cylinder with no heat transfer (termed "theoretical air flow") is directly proportional to the absolute inlet-air temperature. The straight lines drawn through the origins of figures 1 to 5 show this variation of the theoretical air flow with the inlet-air temperature.

If M equals the mass of air inducted into the cylinder, then

$$\frac{1}{M} = \alpha T_c = \alpha T_a B + \alpha T_w (1 - B)$$

or

$$\frac{1}{M_{theoretical}} = \alpha T_c = \alpha T_a$$

in which α is a constant. It follows from these two equations that αB is the slope of the experimental air-consumption line and α is the slope of the theoretical air-consumption line. The ratio of these two slopes is B.

The values of B and $1 - B$ for the different cylinders were calculated from figures 1 to 5 and are given in the following table:

Cylinder	B	1 - B
17.6 engine	0.446	0.554
CFR engine	.492	.508
Lycoming O-1230	.613	.387
Allison V-1710	.655	.345
Wright 1820 G200	.670	.330

Equation (3) shows that, if the $\log_e \frac{1}{B}$ is plotted against the reciprocal of the cube root of the cylinder displacement, the data for geometrically similar cylinders should fall on a single straight line passing through the origin. The data from the preceding table were plotted by this method in figure 6. The data fall surprisingly close to a straight line passing through the origin. The heating of the cylinder charge is, therefore, more dependent upon cylinder size than upon cylinder design. Figure 7 is a replot of figure 6 in a more useful form.

The slope of the line in figure 6 is 2.32 and the equation relating B and cylinder displacement D is therefore

$$\log_e \frac{1}{B} = \frac{2.32}{\sqrt[3]{D}} = \log_e \frac{T_w - T_a}{T_w - T_c}$$

Approximations. - The test methods used in this investigation do not take into account the heating of the charge through admixture with hot residual gases. If the specific heat of the residuals equals the

specific heat of the charge, the temperature of the residuals will not affect the volumetric efficiency and, consequently, this heating effect is not detectable in the data obtained. The heating due to residuals must be estimated by other means.

Pressure loss in the induction process causes a rise in charge temperature. The test method used in this report takes this temperature rise into account, but equation (2) was derived on the assumption that all heating is caused by heat transfer. As a consequence, the form of equation (2) is not exactly correct, but the errors introduced by this approximation are small.

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APPENDIX

EQUATION FOR CHARGE TEMPERATURE

Notation. - The following symbols will be used in the derivation of formulas for determining the cylinder-charge temperature:

Q quantity of heat transferred to charge

K mean coefficient of heat transfer from cylinder wall to charge

ΔT temperature differential between cylinder wall and cylinder charge $(T_W - T_c)$

T_W inside temperature of cylinder wall

T_c temperature of cylinder charge

T_a temperature of inlet air

C heat capacity of entire cylinder charge per degree change in temperature

t time of contact between cylinder wall and charge

N engine speed, revolutions per unit time

k proportionality constant between t and $\frac{1}{N}$

B dimensionless parameter $\left(\frac{-kK}{CN} \equiv \log_e B\right)$

D engine displacement

Derivation of equation. - The charge drawn into the cylinder is heated by heat transfer from the cylinder walls. The heat-transfer equation is

$$dQ = K\,\Delta T\,dt \qquad (4)$$

The rise in the temperature of the cylinder charge, assuming the cylinder-wall temperature to be constant, is

$$dT_c = -d\Delta T = \frac{dQ}{C} \qquad (5)$$

Eliminate dQ from the two equations

$$C\,d\Delta T = -K\,\Delta T\,dt$$

$$\frac{d\Delta T}{\Delta T} = -\frac{K}{C}\,dt$$

Integrate the preceding equation, assuming that K and C are constant,

$$\log_e \Delta T = -\frac{K}{C}\,t + C_1$$

where C_1 is the integration constant. The constant may be evaluated by assuming that, when t equals zero,

$$\Delta T = T_w - T_a$$

Therefore,

$$C_1 = \log_e (T_w - T_a)$$

At any other time

$$\Delta T = T_w - T_c$$

Substitute the values of C_1 and ΔT into the equation

$$\log_e \frac{T_w - T_c}{T_w - T_a} = -\frac{K}{C}\,t$$

The time t is inversely proportional to engine speed. Therefore,

$$\log_e \frac{T_w - T_c}{T_w - T_a} = -\frac{kK}{CN}$$

or

$$\frac{T_w - T_c}{T_w - T_a} = e^{-\frac{kK}{CN}} = B$$

Also

$$T_c = T_a B + T_w (1 - B) \tag{6}$$

Equation (6) is the basic equation for relating cylinder-charge temperature to inlet-air temperature and cylinder-wall temperature and is the same equation as given in reference 1 except that the constants are defined differently, that is, $B = 1 - A$.

The ratio K/C is proportional to the surface-volume ratio at constant pressure. The surface-volume ratio of similar cylinders varies inversely with the cube root of the displacement; therefore,

$$\frac{K}{C} \propto \frac{1}{\sqrt[3]{D}}$$

or

$$\log_e B = -\frac{H}{\sqrt[3]{D}}$$

and

$$\log_e \frac{1}{B} = \frac{H}{\sqrt[3]{D}} \tag{7}$$

where H is the proportionality constant.

If $\log_e \frac{1}{B}$ is plotted against $\frac{1}{\sqrt[3]{D}}$ for various engines, the data should fall on a straight line passing through the origin with a slope equal to H.

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1. Taylor, C. Fayette, and Taylor, Edward S.: The Internal Combustion Engine. International Textbook Co. (Scranton, Pa.), 1938, p. 256.

2. Sanders, Newell D.: Effect of Fuel Vaporization, Inlet-Air Temperature, and Fuel-Air Ratio on the Knock Limit of Isooctane. NACA ARR, Nov. 1942.

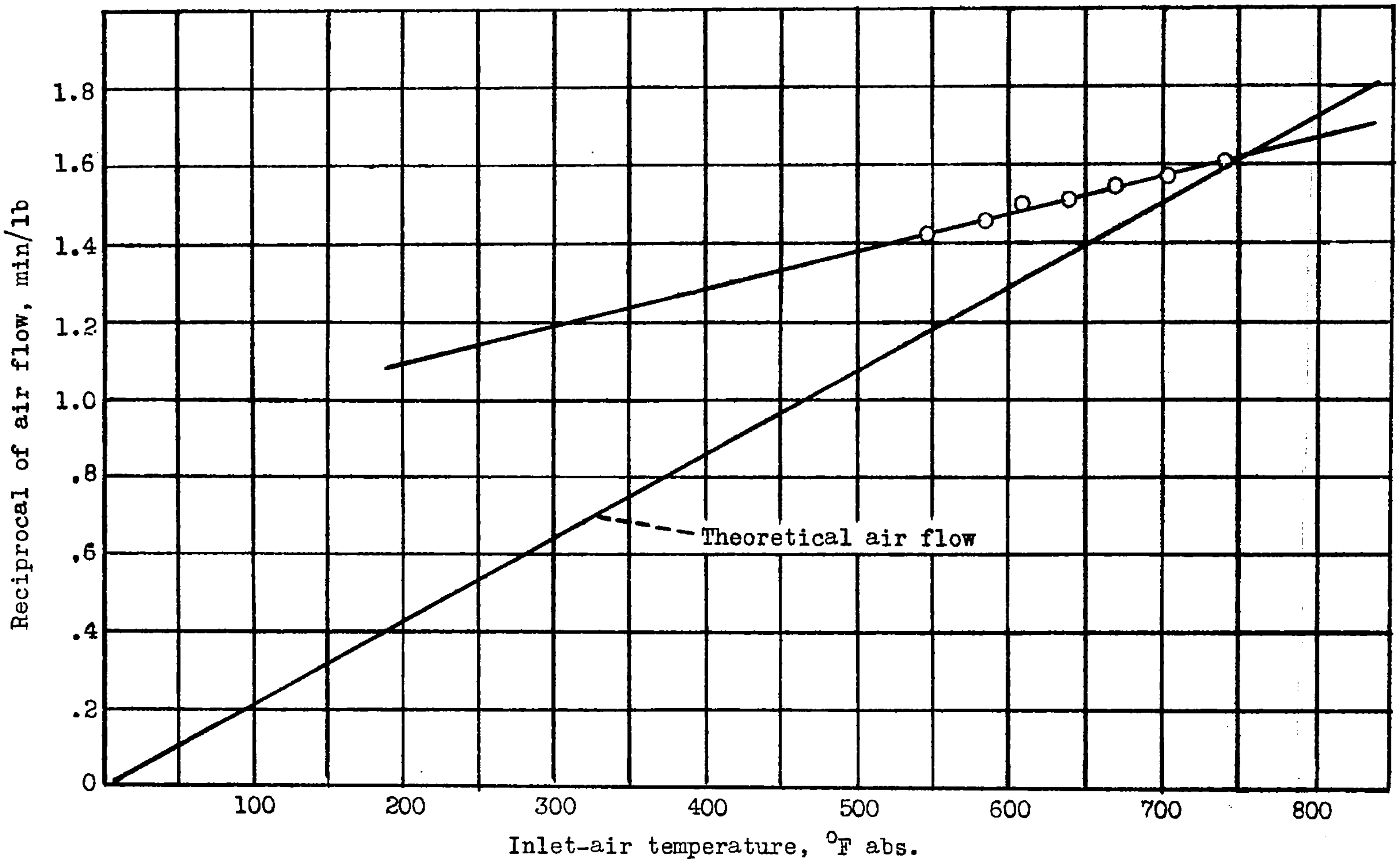

Figure 1.- Comparison of theoretical and measured air flow in a 17.6 engine. Engine displacement, 17.6 cubic inches; compression ratio, 7.0; intake valve closes, 40° A.B.C.; engine speed, 2370 rpm; inlet-air pressure, 29.07 inches Hg absolute; exhaust pressure, 30 inches Hg absolute; coolant temperature, 250° F; fuel-air ratio, 0.075.

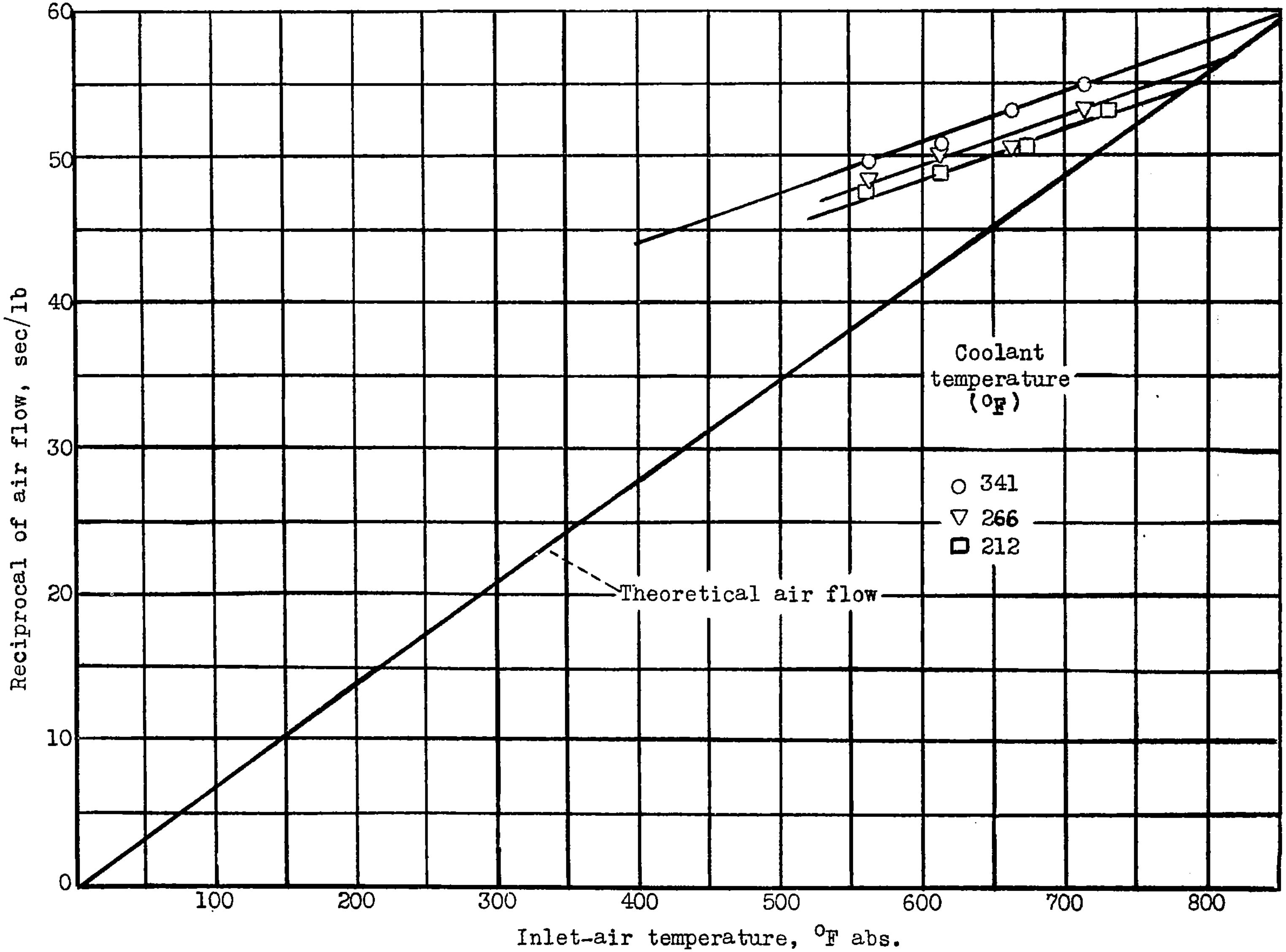

Figure 2.- Comparison of theoretical and measured air flow in a CFR engine. Engine displacement, 37.4 cubic inches; compression ratio, 7.0; intake valve closes, 34° A.B.C.; engine speed, 2000 rpm; inlet-air pressure, 30 inches Hg absolute; exhaust pressure, 30 inches Hg absolute; fuel-air ratio, 0.075.

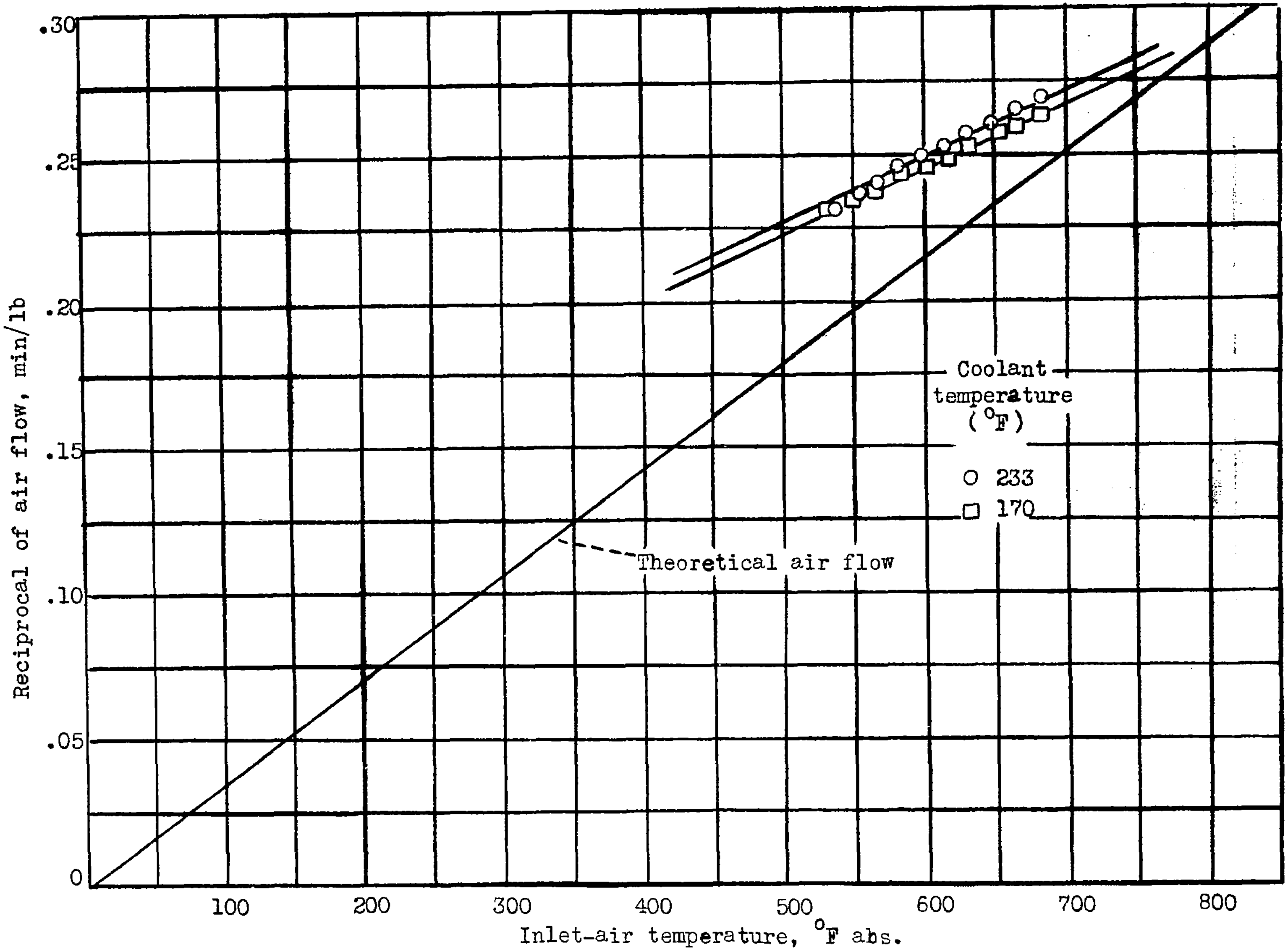

Figure 3.- Comparison of theoretical and measured air flow in a Lycoming O-1230 cylinder. Engine displacement, 102.8 cubic inches; compression ratio, 7.0; intake valve closes, 67° A.B.C.; engine speed, 2400 rpm; inlet-air pressure, 29.20 inches Hg absolute; exhaust pressure, 30 inches Hg absolute; fuel-air ratio, 0.075.

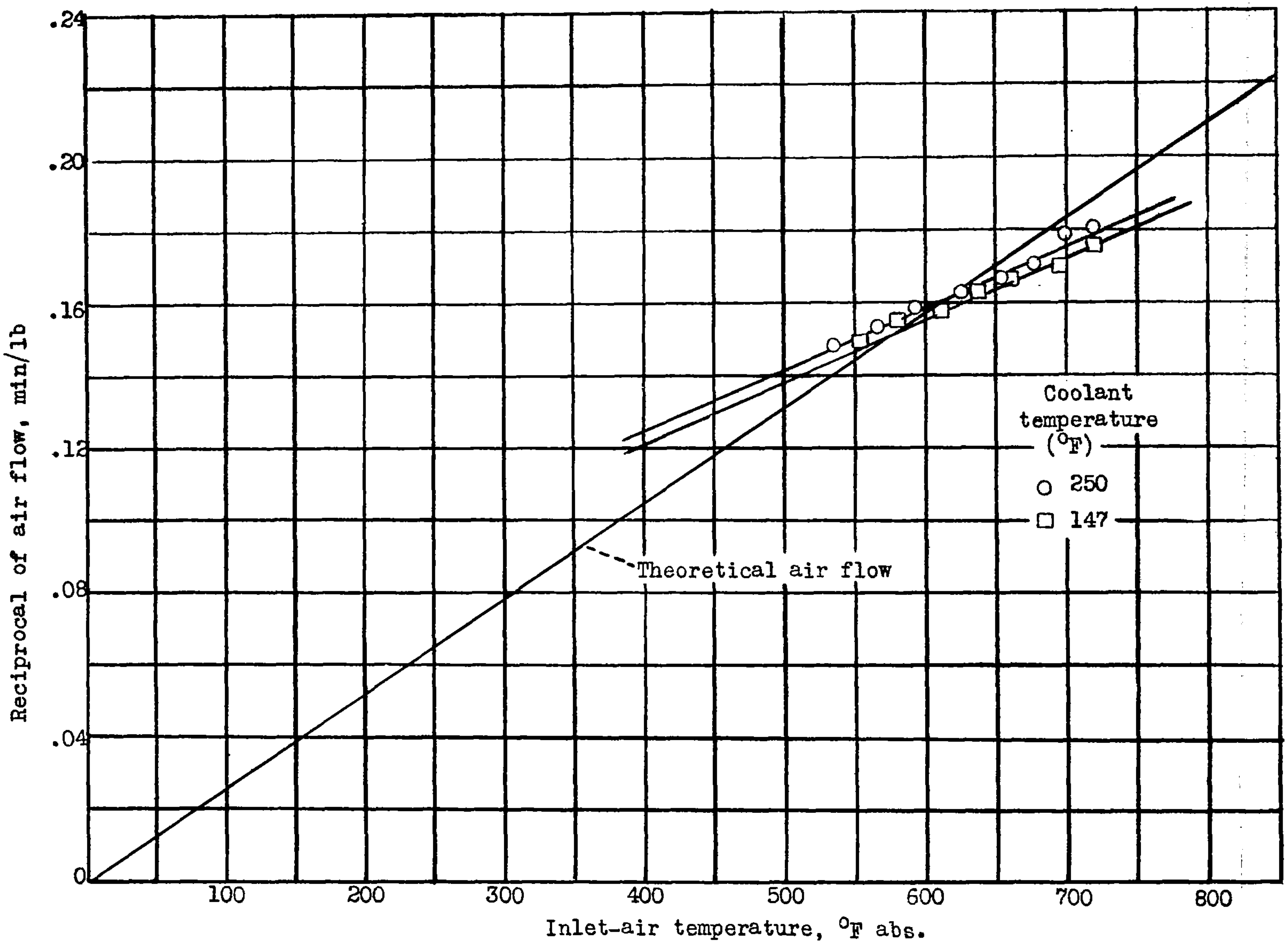

Figure 4.- Comparison of theoretical and measured air flow in an Allison V-1710 cylinder. Engine displacement, 142.5 cubic inches; compression ratio, 6.65; intake valve closes, 62° A.B.C.; engine speed, 2400 rpm; inlet-air pressure, 29.10 inches Hg absolute; exhaust pressure, 30 inches Hg absolute; fuel-air ratio, 0.08.

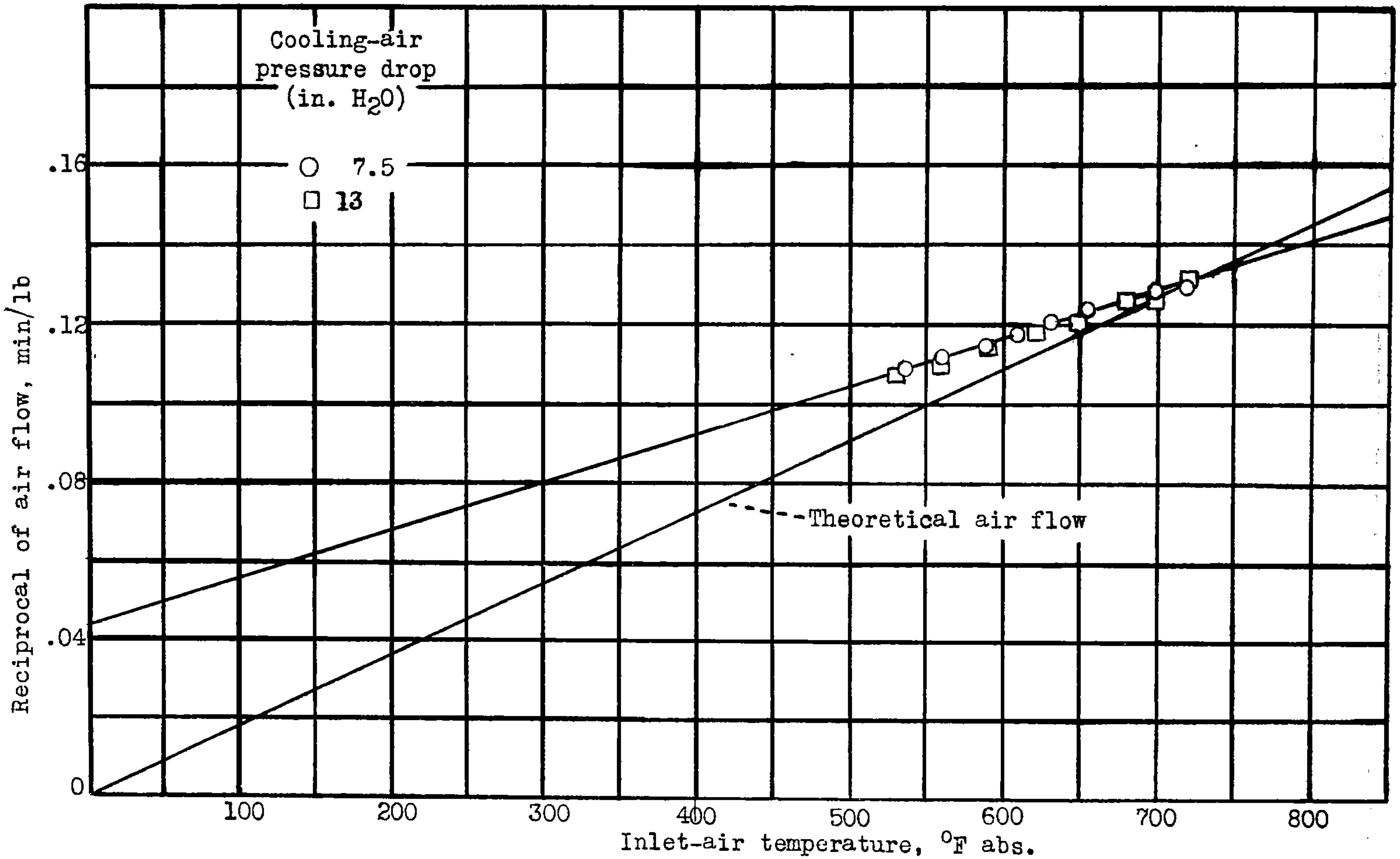

Figure 5.- Comparison of theoretical and measured air flow in a Wright 1820 G200 cylinder. Engine displacement, 202.5 cubic inches; compression ratio, 6.72; intake valve closes, 40° A.B.C.; engine speed, 2400 rpm; inlet-air pressure, 29.3 inches Hg absolute; exhaust pressure, 30 inches Hg absolute; fuel-air ratio, 0.075.

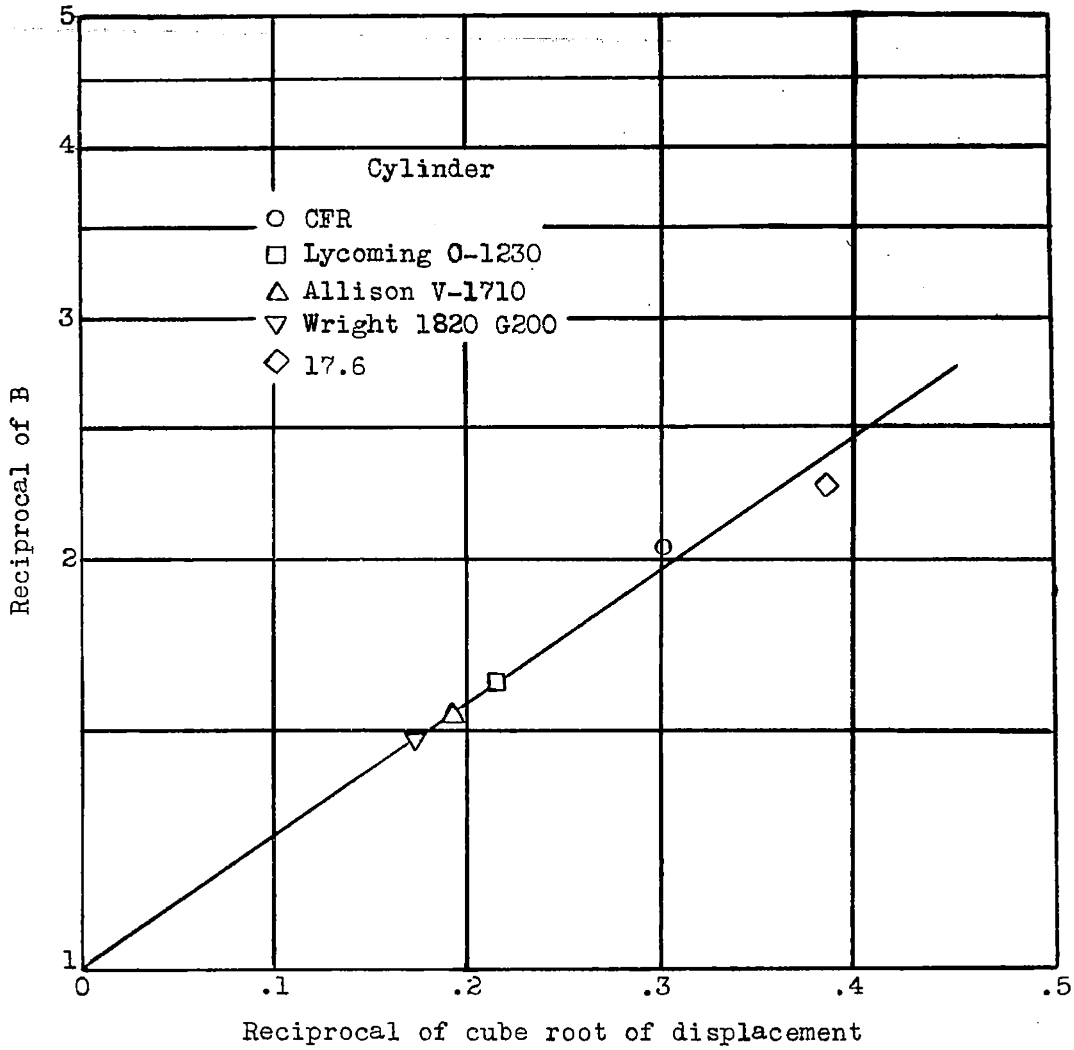

Figure 6.- Effect of cylinder displacement on heating of cylinder charge.

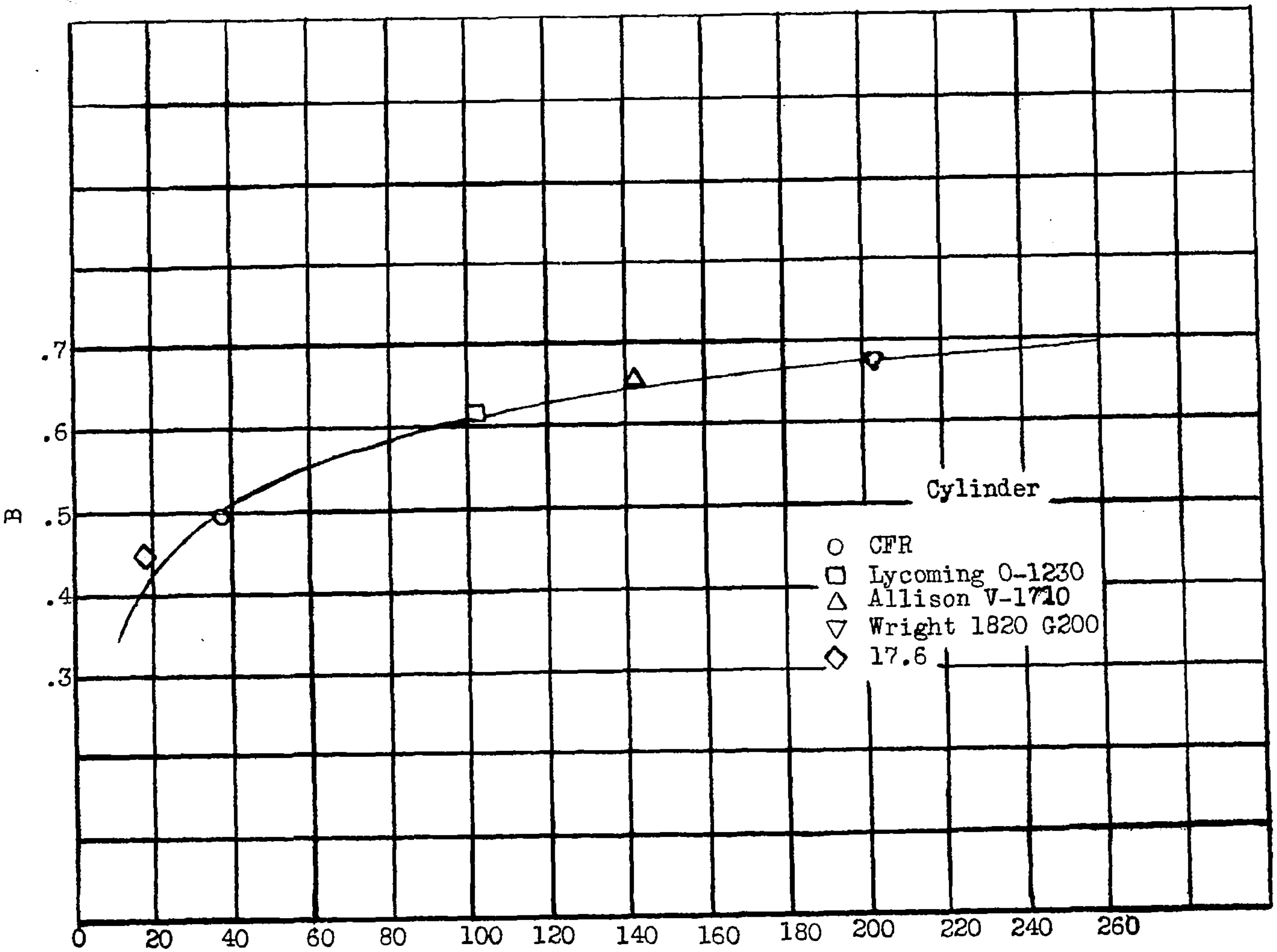

Figure 7.- Effect of cylinder displacement on heating of cylinder charge.